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UNIAXIAL NEUTRAL DENSITY CRANIAL ACCELEROMETER DESIGN

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SUMMARY

This paper is a feasibility study of implanting neutral density accelerometers into the brain of human cadavers to measure brain motion relative to that of the skull. Because there is but one set of data, little emphasis can be placed upon the numerical information received. More important are the general observations that serve as input for further study. Specifically, it is feasible to construct a compact transducer that will measure accelerations of the brain relative to the skull. Also, it appears that the brain and skull experience differential motion under impact conditions. It seems the brain exhibits some viscoelastic damping effects as well.

The results of this study suggest that there is great potential for gaining valuable insight into the mechanics of head trauma from this neutral density method of determining acceleration. However, much more data are required, and much more development is desired before the technique becomes fully workable. The approach shows great promise and should be investigated further.

FOREWORD

Trauma is the leading cause of death for Americans between the ages of 1 and 44. In fact, in the United States alone, there are 60,000 deaths per year which result from traumatic brain injury. Brain injuries are present in 75% of all road traffic deaths (Seelig and Marshall). It is arguable, therefore, that the understanding of the mechanics of brain injury holds great social significance. At present, however, little is known concerning the event time histories of head injury. It is with this in mind that a uniaxial neutral density cranial accelerometer is designed, fabricated, and tested. The objective is to examine the feasibility of such a device, and to determine if future study is warranted. Such a transducer would be instrumental in the investigation of relative translations and rotations of brain tissue.

BACKGROUND

Closed head injuries may result from either angular or translational accelerations and produce injuries such as cerebral concussions, contusions, lacerations, and torn bridging vessels. In essence, brain damage is a result of direct contact or inertial loads. According to Gurdjian (1968), the effects of contact impact and/or acceleration of the brain can be described as follows:

1. Direct brain contusion from skull deformation at the point of contact (coup injury),

2. Indirect contusion produced by a negative pressure on the opposite side of impact (countrecoup injury),

3. Brain deformation as it responds to pressure gradients which causes shearing stresses at the cranio-spinal junction,

4. Brain contusion from movements of the brain against rough and irregular interior skull surfaces, and

5. Subdural hematoma from movement of the brain relative to its dural envelope resulting in tears of connecting blood vessels.

Linear accelerations are assumed to produce brain damage according to the "Pressure gradient - cavitation hypothesis". These injuries result from the development of large pressure gradients generated by the propagation of steep frontal waves following impact. The absolute motion of the brain and the relative displacement with respect to the skull produce the following consequences:

1. Development of shear stresses near the brain stem,

2. Collapse of cavitation bubbles which are formed when the local pressure at the countrecoup site is less than or equal to the brain fluid vapor pressure,

3. Separation of the brain from the cranial wall, and

4. Generation of neurovascular friction.

More specific to the nature of this study, brain movement relative to the skull was studied (Holbourn (1943) and Gurdjian (1968)). It was hypothesized that the brain tissue is rather incompressible and translational acceleration is harmless, however, rotational acceleration could develop tensile and shear strains. It was thought that rotational head acceleration would be the same whether such an acceleration was produced through direct frontal impact or through an indirect loading such as inertial loading of the head during whiplash. Ommaya and Hirsch (1971) found rotational motion to be more critical to brain injury than translational motion. Unterharnscheidt (1969) studied brain injuries sustained from translational and rotational accelerations. As aforementioned, it appears that pure translational acceleration results in the development of pressure gradients while injuries resulting from rotational acceleration appear as shear stress. Roberts, Hodgson and Thomas (1966) found significant shear strain on the brain stem in translational as well as rotational impacts. However, no current data sustains any correlation between brain injury to translational motion of the head from short duration force impacts whether direct or indirect in nature. Hence, the need for quantifying the translational acceleration of brain relative to the skull necessitates further study.

METHODOLOGY

The difficulties associated with the study of head trauma are complex and diverse. The task of developing a transducer for investigation of brain injury mechanisms is arduous when little is understood about the material properties and behavior of the brain. Therefore, many assumptions must first be made concerning the design criterion of such a device, the method of implantation and simulation of injury, and the type of information to anticipate from the data.

The determination of localized brain accelerations is of particular importance to the understanding of neurological trauma, especially in closed head injury. It is with this in mind that a uniaxial neutral density cranial accelerometer is designed. The primary consideration is to inhibit any relative motion with respect to surrounding brain tissue. To accomplish this, the transducer must have the same density as human cadeveric brain and must have a non-hydrodynamic geometry. It must resist independent translation and rotation from all perspectives, i.e. it must move with the brain. The device must also be water-tight and rigid to resist the harmful environment of the body under repeated use. The volume of the transducer must be minimized to facilitate implantation of one or more accelerometers without appreciably compromising the integrity of the brain or skull.

Ideally, the transducer should be implanted in the human cadaver and the test be run as quickly as possible after the subject's death. Care should be taken during implantation to assure that a minimum of air is introduced subdurally, and that unwanted gas is 'bled' from the cerebrospinal fluid. Post implantation, the dura, skull and scalp must be sealed, and the arterial, venous, and nervous (CSF) systems must be pressurized. A stereotactic unit was used for pre- and post-impact x-ray positioning. To reference the behavior of the brain an extracorporeal accelerometer must be mounted to a corresponding area of the skull, having the same orientation as the cranial transducer.

Of greatest interest is any relative motion between the brain and skull that occurs. This motion is analyzed in terms of accelerations and displacements. Also of importance are amplitude, frequency, and phase differences between the brain and skull acceleration time histories. An attempt is made to explain the significance of the results.

EXPERIMENTAL APPROACH

Initially, a non-functional biaxial prototype was developed to investigate the feasibility of a neutral density acceleromter, as shown in Figure 1. It was found that the unit did maintain its position relative to surrounding brain tissue and that the size was not prohibitive. It was therefore suggested that a

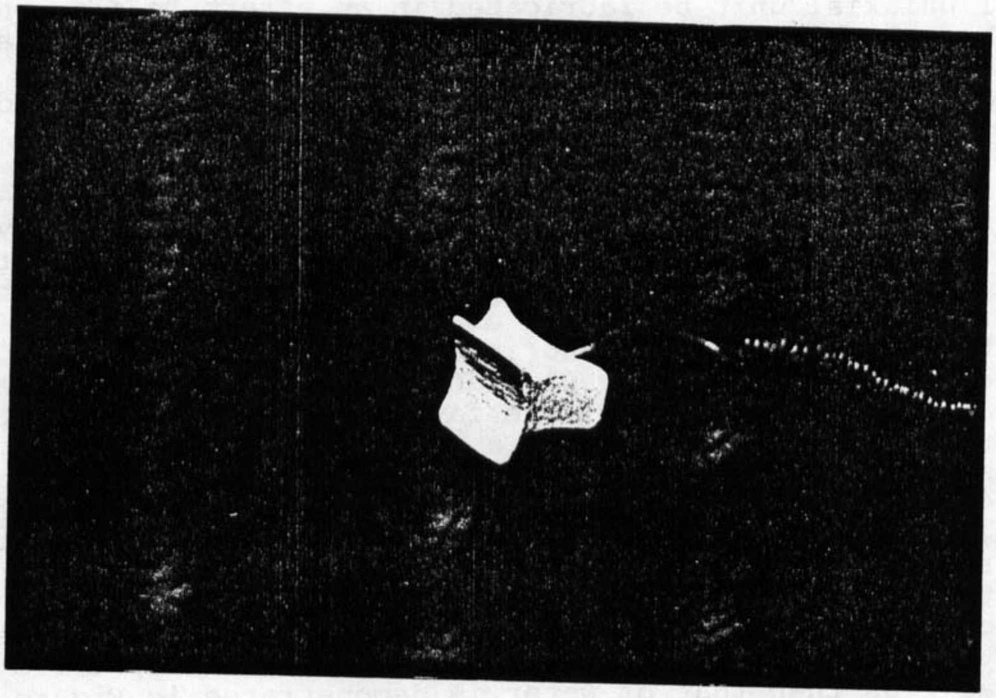


Fig. 1 Biaxial neutral density accelerometer - non-working prototype

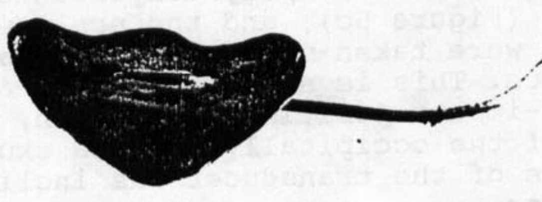


Fig. 2 Iniaxial neutral density design concept

functional uniaxial unit be fabricated in an effort to discern whether the data obtained from such a device would be credible. The subsequent proceedure involved three distinct stages; the design and construction of the uniaxial unit, the surgery, and the impact itself.

The design of the uniaxial neutral density accelerometer (NDA) centered around an Endevco model 2264-200 piezo-resistive accelerometer. A preliminary design concept is shown in Figure 2. As the accelerometer was quite large and far too dense, the mounting flanges were machined off of the casing. After experimentation with plastics and injection foams it was decided that, like the prototype, the NDA transducer housing should be made of balsa wood. Because of the favorable performance of the prototype its geometry was used as a guide for the NDA design. After consideration of several clay models the balsa housing was shaped and the accelerometer was glued in place via a central aperature, strict attention being paid to the orientation of the transducer's sensitive axis. After the entire structure was coated with a rubberized spray compound, the transducer had a final specific gravity of 0.71, and a volume of 1.122 ml. The completed unit is shown in Figure 3. That its final specific gravity was less than that of water is demonstrated in Figure 4. The excitation and data wires were not coiled in this instance, but will be in the future, to avoid tension effects. A list of the densities of the various materials used can be found in Table 1.

The neutral density accelerometer was implanted through a 25-mm diameter trephine in the parietal foramen of a human cadaver skull. A cruciate incision was made in the dura and a 38 mm linear incision was made in the gray matter of the parietal lobe. The transducer was inserted into the incision (Figure 5a) so that it was located as close to the mid-line as possible while avoiding any sulci or ventricles. After the incised brain tissue surrounded the implant, the cerebrospinal fluid was bled by means of a spinal catheter. Normal saline was then injected and the dura was sutured closed. A thin layer of silastic was applied to the sutured dura (Figure 5b), polymethylmethacrylate was used to fill the trephine (Figure 5c), and the scalp was sutured closed. Pre-impact x-rays were taken using an ACE halo #3 as a stereotactic device. This is shown in Figure 6. X-rays were used for pre- and post-impact position comparison, and to determine the orientation of the occipitally mounted skull accelerometer. The sensitive axis of the transducer was inclined at 38 deg to the Frankfort plane.

Prior to impact, a skull accelerometer was mounted on the occipital bone and positioned at 38 degrees from the Frankfort plane so that data from the implanted transducer those from the skull accelerometer could be compared. The cadaver was impacted facially along the Frankfort plane at 21.4 g with a linear pneumatic impactor. The acceleration time trace for the impactor is shown in Figure 7. The cadaver was subjected to three additional impacts (non-facial) prior to obtaining the post-

Table 1

LIST OF MATERIAL DENSITIES

Balsa with rubber compound	0.17 g/ml
Epoxy	1.56 g/ml
Accelerometer (machined)	2.74 g/ml
Brain (whole)	1.00 g/ml
(regional frozen/thawed cadaveric)	0.80 g/ml
NDA Transducer	0.71 g/ml

Fig. 3 Uniaxial neutral density accelerometer - working prototype

Fig. 4 Demonstration of neutral density accelerometer in water

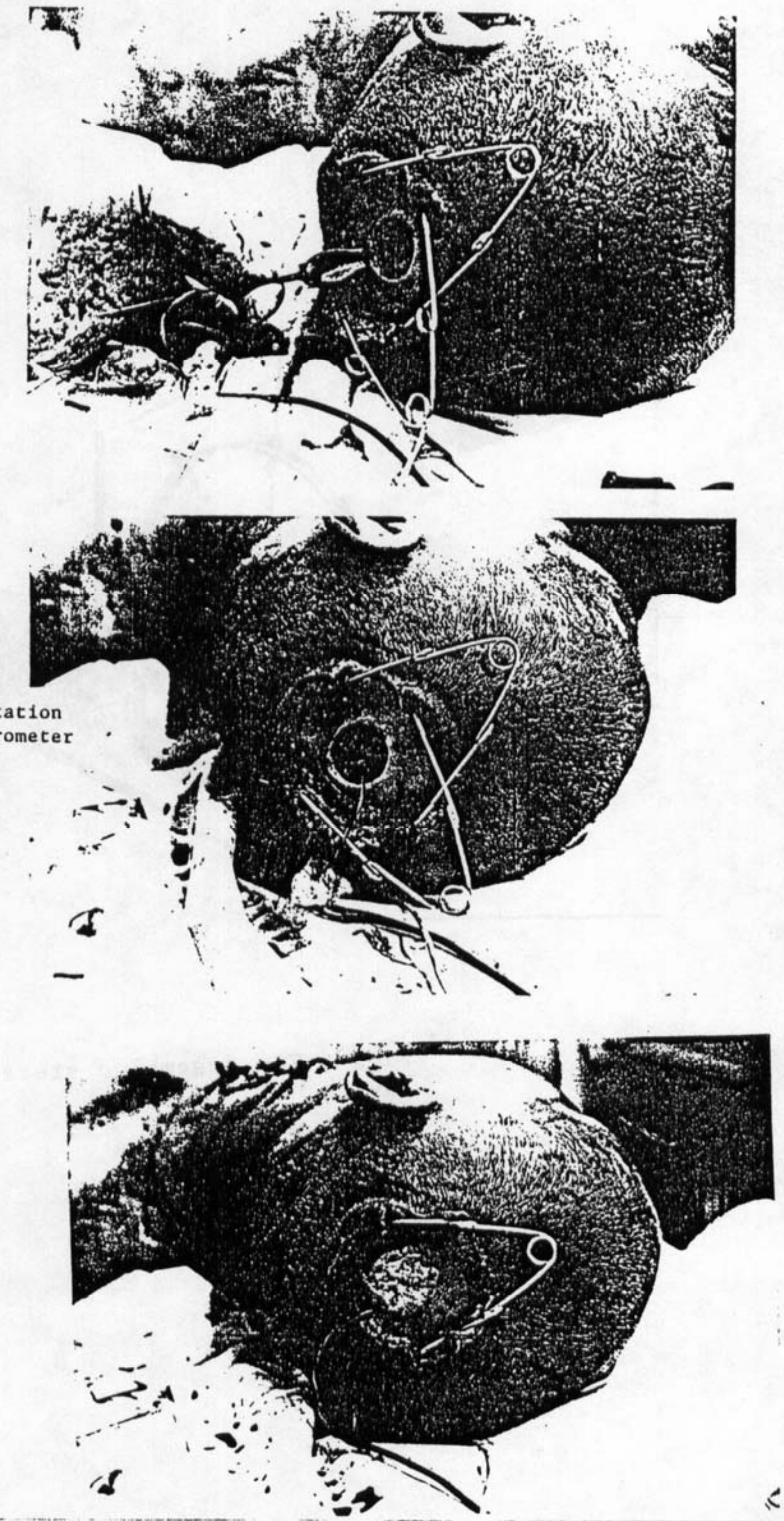


Fig. 5 Procedure for Implantation of a neutral density accelerometer in a cadaveric skull

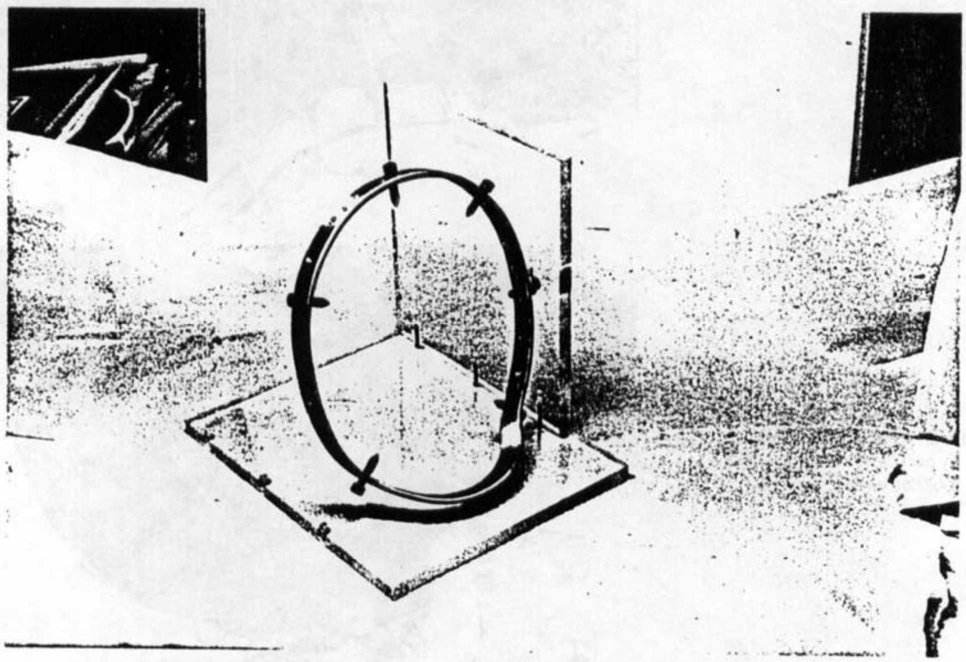


Fig. 6 The assembled stereotaxic device

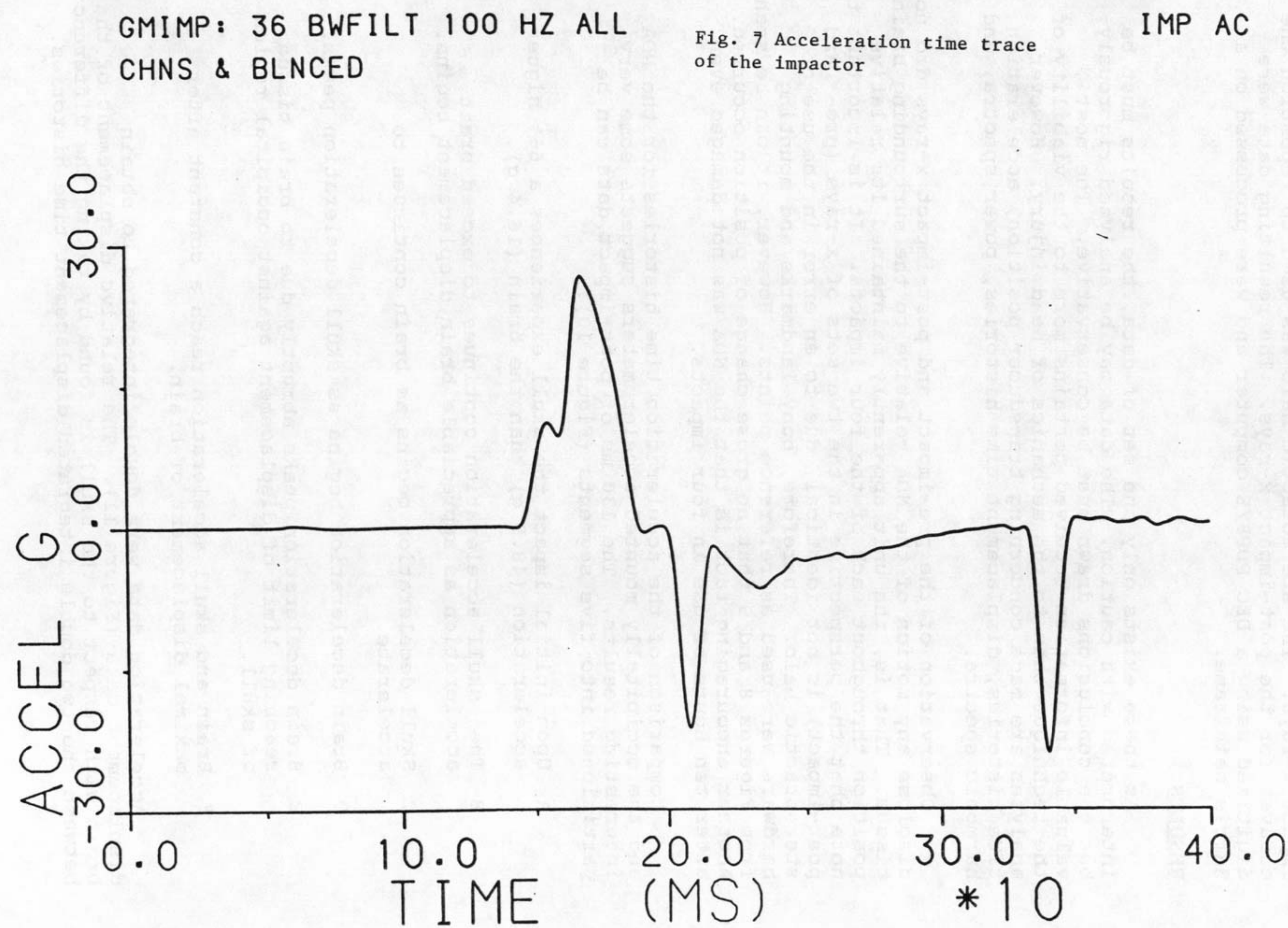


Fig. 7 Acceleration time trace of the impactor

impact x-rays. The stereotactic halo was used to repostion the cadaver for the post-impact x-rays. The resulting data were digitized using a DEC PDP8/E computer and were processed on a Harris mainframe.

RESULTS

As there exists only one set of data, the results must be interpreted with caution. The data may be analyzed rigorously, but the conclusions drawn must be conservative. The most valuable information received pertains more to the viability of the technique than to the mechanics of head injury. However, analyses are made concerning transducer position, acceleration time histories, displacement time histories, power spectra, and harmonic spectra.

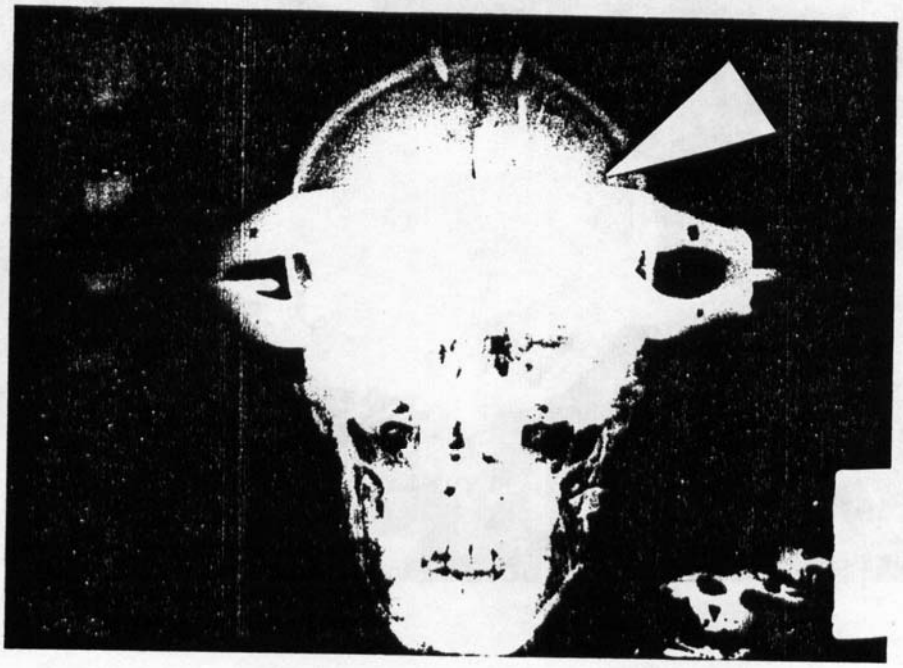
Observation of the pre-impact and post-impact x-rays did not disclose any motion of the NDA relative to the surrounding brain tissue. That is, the unit apparently maintained its relative position throughout each of the four impacts. It is important to note that the perspective in the two sets of x-rays (pre- and post-impact) is not identical, due to an error in the use of stereotactic halo. Therefore, bony landmarks and mounting hardware were used as reference points. However, it can be seen from Figures 8 and 9 that no gross change of position occurred. Another encouraging fact is that the NDA was not damaged even after ten hours of use in four impacts.

Comparison of the acceleration time histories for the NDA and the occipitally mounted accelerometers suggests some very interesting results. The 130 ms of post-impact data can be partitioned into five segments (Figure 10):

- A Upon initial impact the skull experiences a 66% higher acceleration (48.5 g) than the brain (16.4 g).
- B The skull acceleration continues to exceed brain acceleration as appreciable brain displacement begins.
- C Skull deceleration begins as brain continues to accelerate.
- D Brain deceleration begins as skull deceleration peaks.
- E Brain deceleration peaks abruptly due to brain tissue reaching limit of displacement against occipital region of skull.
- F Brain and skull acceleration reach a constant after maximal displacement of brain.

Acceleration data were double integrated to obtain displacement data (Figure 11). The relative displacement of the brain with respect to the skull is found by taking the difference between the two double integrated displacement time histories.

ANTERIOR-POSTERIOR VIEW

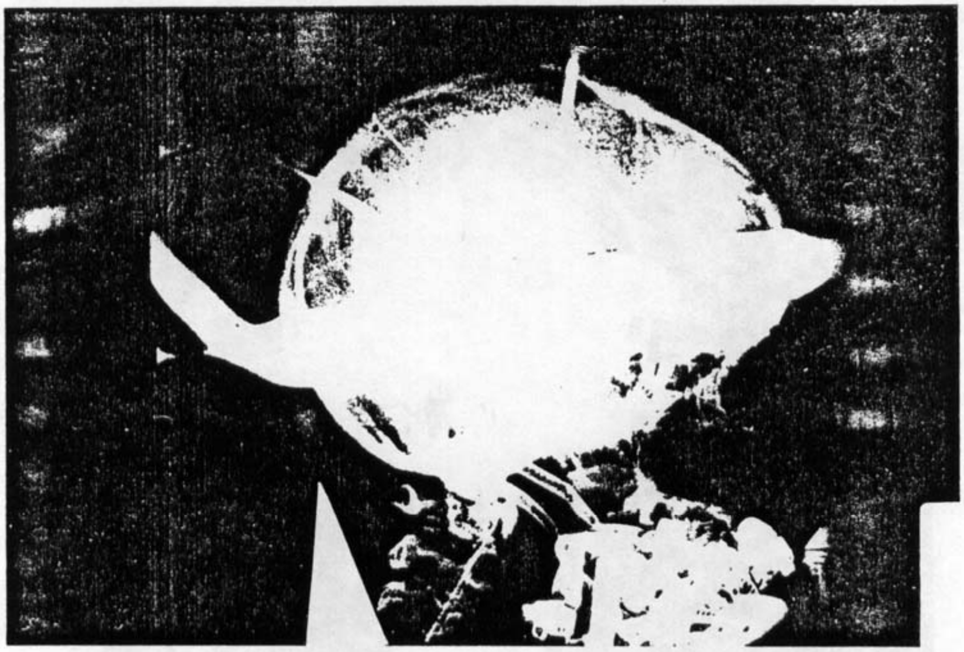


Pre-impact

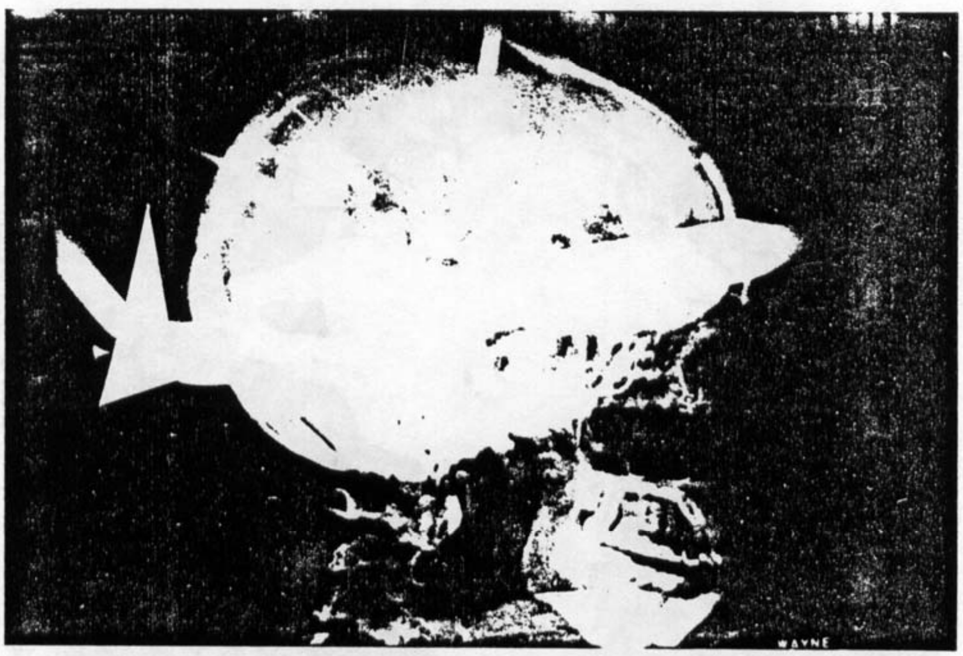
Post-impact

Fig. 8 Pre and post-impact views of the skull showing position of the neutral density accelerometer

LATERAL VIEW



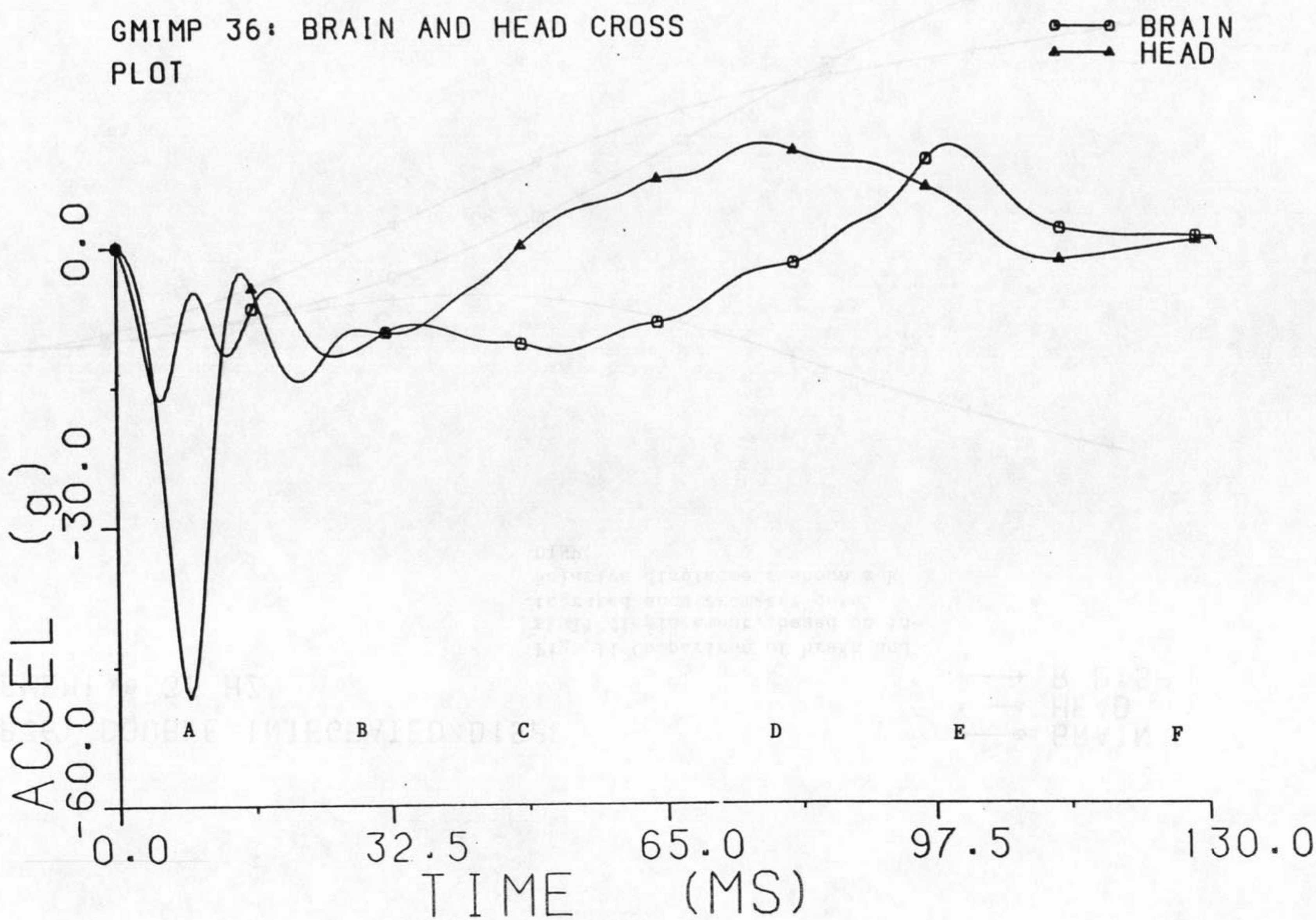
Pre-impact



Post-impact

Fig. 9 Pre- and post-impact lateral views of the skull showing position of the neutral density accelerometer

Fig. 10 Comparison of brain and skull accelerometer output



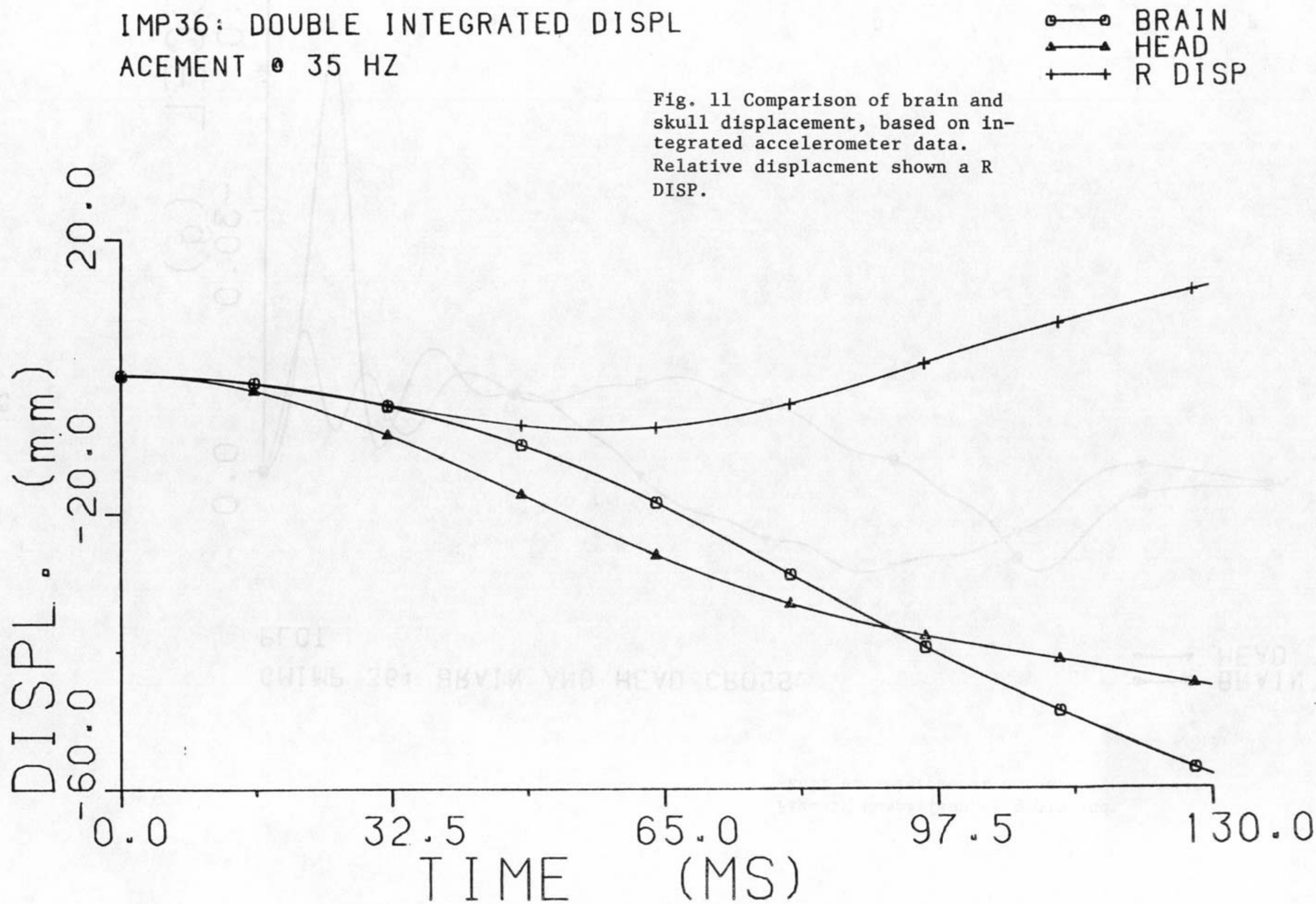


Fig. 11 Comparison of brain and skull displacement, based on integrated accelerometer data. Relative displacment shown a R DISP.

The relative anterior displacement of the brain was +8 mm and the maximum posterior displacement was -12 mm, as shown in Figure 12. A comparison of the computed relative displacement with brain and skull accelerations is shown in Figure 13. The fact that there is no trend in the integrated relative displacement data to return to zero, can indicate the presence of some zero shift in the integration process. Other sources of error include non-identical alignment of the sensistive axis of the NDA with that of the occipital transducer, and the transcribing of two different arcs by each of the accelerometers due to a rotational component. Although the displacement values themselves may not be entirely accurate, the fact that relative motion did occur is important.

Correlations using Simpson's method of numerical integration were performed to generate power spectra. An auto correlation of the skull acceleration was compared to a cross correlation of the brain and skull acceleration in Figure 14. This showed that the brain power spectrum lagged that of the skull by 19.5 ms, or 35.1 deg, if a period of 360 deg is assumed for the data window.

A Fast Fourier Transform analysis shown in Figure 15 revealed that the magnitudes of the coefficients of the higher order harmonics were greatly reduced for the brain as compared to the skull acceleration data. The energy in the skull was cioncentrated at 8 Hz, while for the brain it was at 4 Hz. Even though the magnitudes of the coefficients are quite different, the frequency spectra patterns are nearly identical, giving the brain acceleration the appearance of being a filtered version of the skull acceleration.

CONCLUSION

The most significant conclusions that can be drawn from this investigation are the simplest. First, it is possible to design an implantable transducer that will tolerate repeated use. Second, it is possible to design a compact neutral density accelerometer for use in human cadaver brain. The combination of like density and high coefficient of drag allows the transducer to maintain its position relative to surrounding brain tissue during impact. Third, the displacement data obtained suggests that the the brain does undergo motion different from that of the skull during impact.

Although there exists thus far only one set of data, there are strong indications that the brain may exhibt some viscoelastic damping effects. The peak brain acceleration is 66% less than the peak skull acceleration. There exists an approximately 35 degree phase lag between the brain and skull acceleration time histories, but the general trends are similar. There is less high frequency information in the brain data than in the skull data. Overall, the brain acceleration appears to be a filtered vision of the skull data.

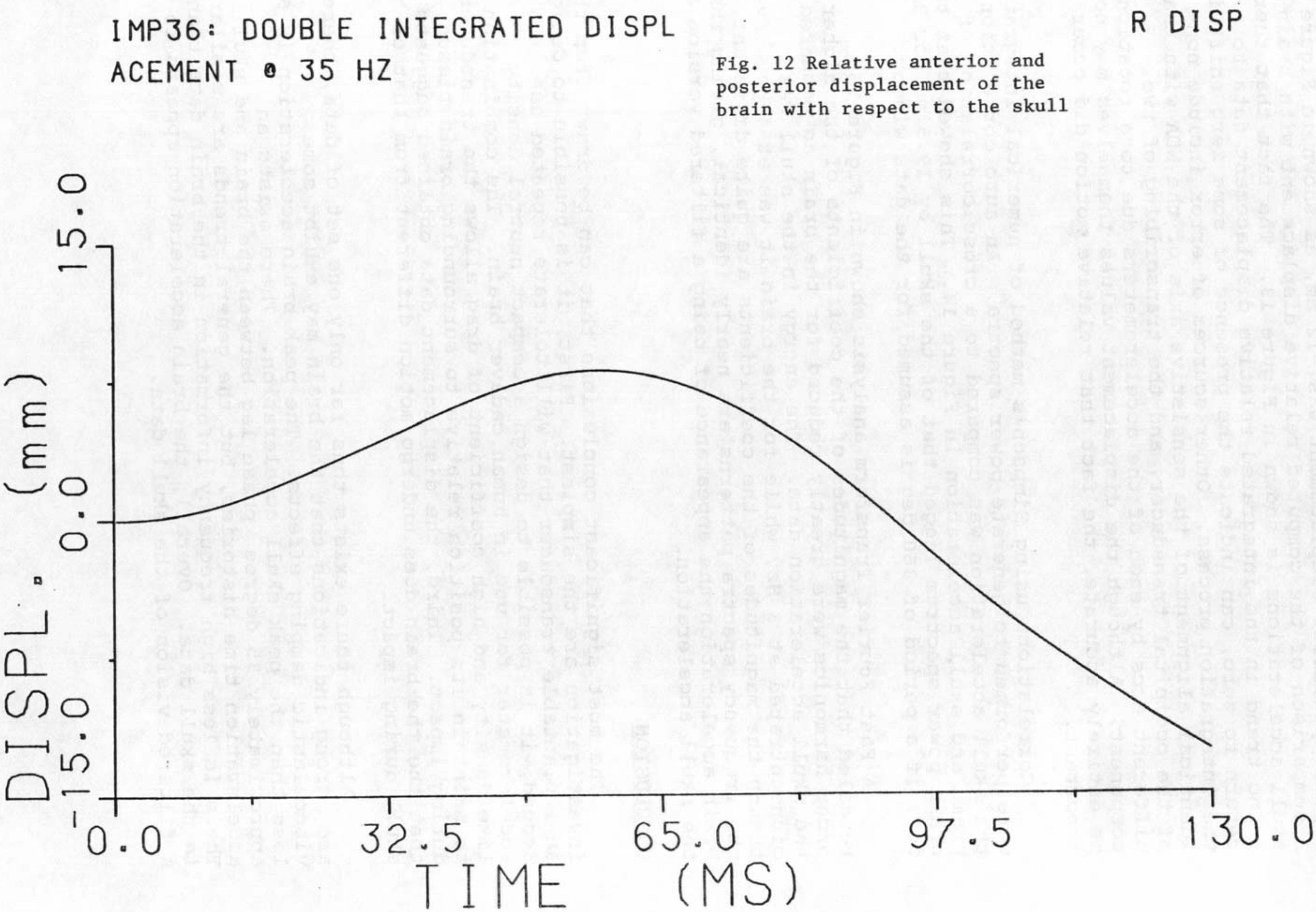


Fig. 12 Relative anterior and posterior displacement of the brain with respect to the skull

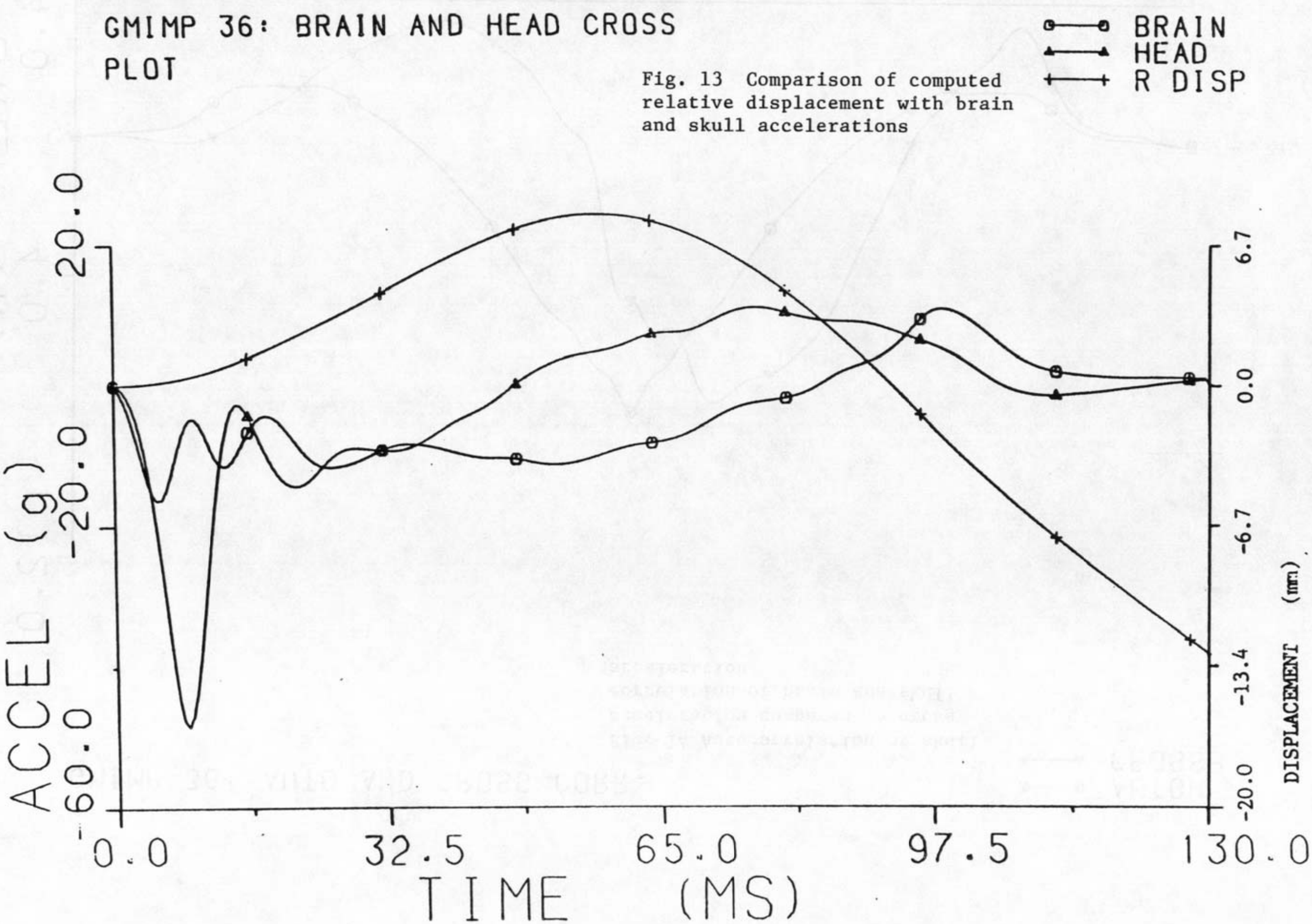


Fig. 13 Comparison of computed relative displacement with brain and skull accelerations

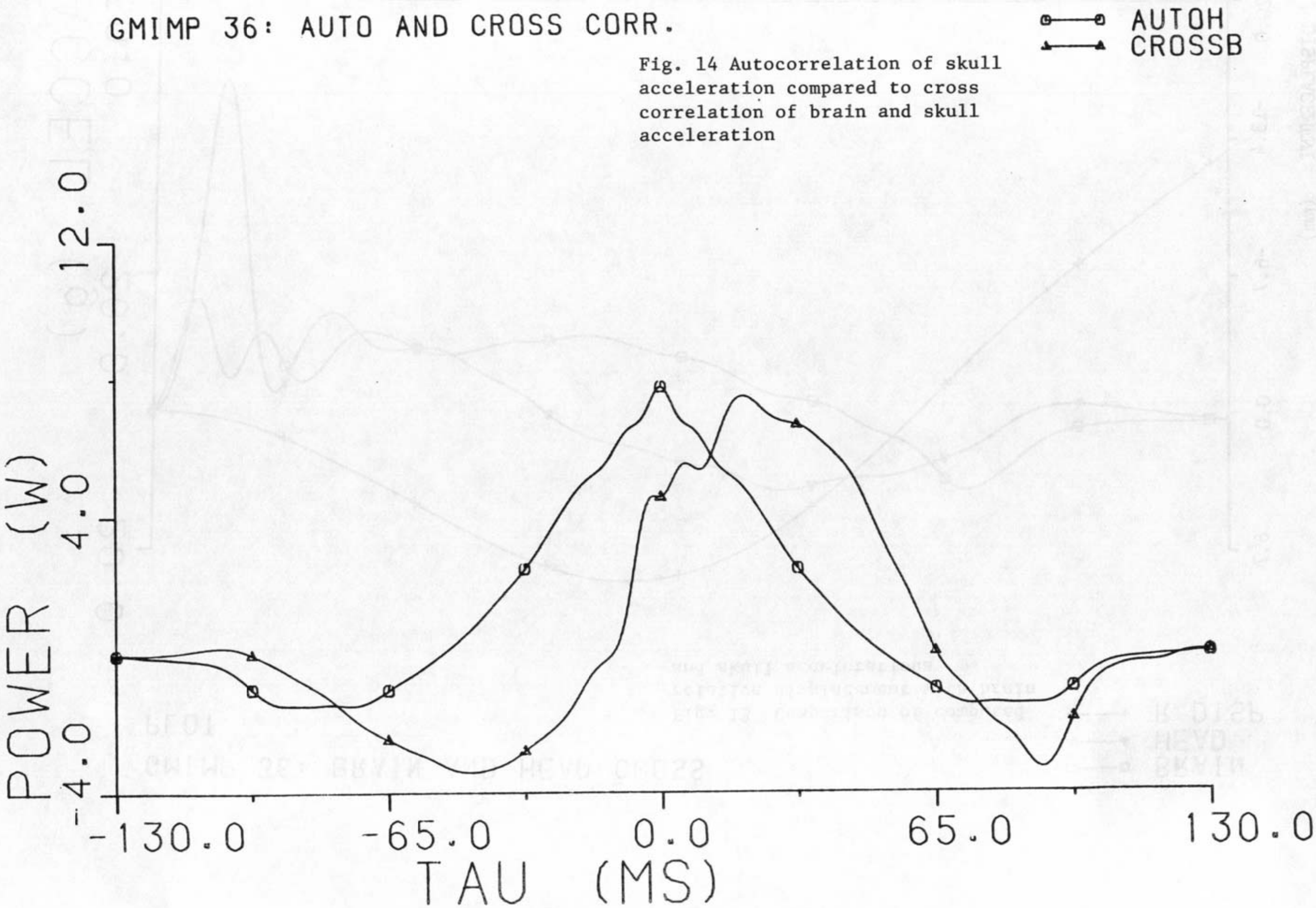


Fig. 14 Autocorrelation of skull acceleration compared to cross correlation of brain and skull acceleration

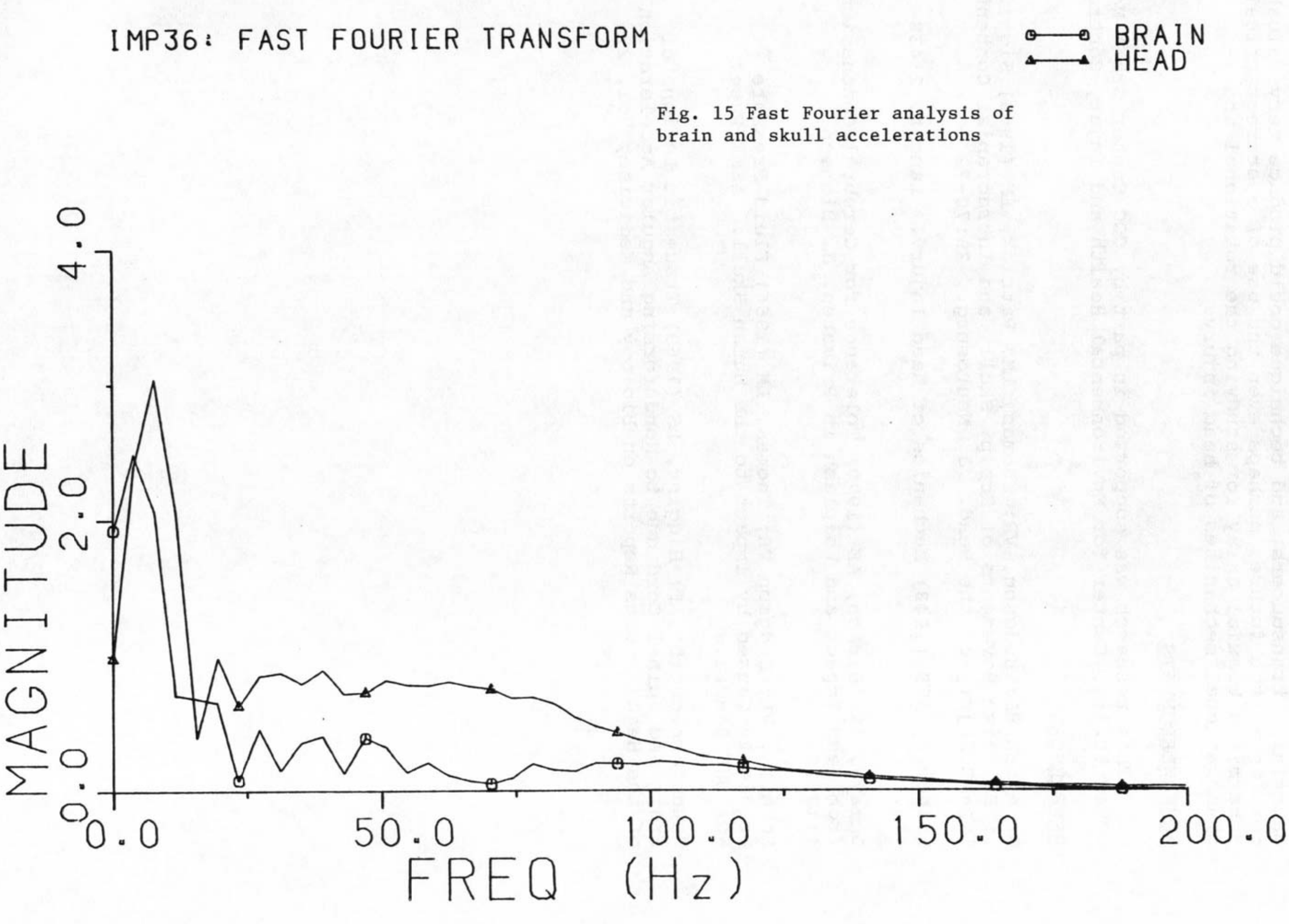


Fig. 15 Fast Fourier analysis of brain and skull accelerations

The data obtained were very encouraging. The need for further testing is self evident. Development and choice of materials, transducers, and technique could produce very valuable results in the future, perhaps even the use of a stereotactically determined biaxial array for studying the rotational and translational mechanisms of head injury.

ACKNOWLEDGMENTS

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DISCUSSION

PAPER: Neutral Density Brain Accelerometer

SPEAKER: Warren Hardy, Wayne State University

Q. John States, University of Rochester
How small can you make these accelerometers? As small as an Endevco 2264? How much can you machine them down? How much do they weigh?

A. I don't recall those figures right off the top if my head. In the future we are not planning on using Endevco 2264. The original prototype actually contained two Entran accelerometer sub-assemblies. I've spoken to some people at Entran and we may be able to come up with a custom sub-assembly mounting.

Q. What would be the minimum volume of your device to get the neutral density? In other words, how small can you make these?

A. It depends on the material that you're using to reduce the density of your accelerometer. The original prototype had a volume of approximately 1 cc. That is relatively small. If you were going to use only four, that might be an appropriate size. Our research has not gotten to the point where we can definitely take a stand and say, "This is how small we can make it." We don't know exactly. We have constructed a device that would work appropriately, if functional, that was on the order of 1 cc. Presumably we should be able to get it smaller.

Comment:
This is a very hopeful effort. The smaller you can make these, the more of them you can put into the brain. I'm sure there are considerable differences in the quality of the brain tissue aside from density that affect this mechanical behavior. By being able to determine its accelerations, you may be able to determine these characteristics.

Q Claude Tarriere, APR
Is this approach compatible with re-pressurization of the brain?

A. Are you asking me if this approach is viable when you repressurize the central nervous system?

Q. Yes.

A. The way that we conduct our tests,the CSF is pressurized to a small degree. I'm assuming that, yes, as long as it is a neutral density or having a density close to that of the brain tissue it should be a viable approach.

Q. So when you cut the brain to introduce the device, after you repressurize you could have a hemmorrhage between the outside of the brain and the location of the device. Otherwise, you could have normal behavior of the brain. Is this a repressurized brain without vascular damage?

A. That would appear to be correct. We pressurize the venous and arterial system as well as the spinal fluid and we would hope that given the pressures that we are introducing into these areas that there is not an appreciable change in the response of the brain tissue after it has been incised or some vessels have been compromised, and as you say there might be hemmorrhage. That would be strickly speculation on my part but that is the assumption we were going on.

Q. Guy Nusholtz, UMTRI
We've done a considerable amount of pressurization of the brain, and one of the things that we've noticed is that when you don't pressurize the brain, almost invariably, there's some form of air between the skull and the brain and when you impact it the brain moves all over the place. It's almost a completely different type of motion similar to what you've seen in your accelerometer compared to the head. But when we pressurize it, we see very little motion occurring, and in fact if you look at the functions between the brain pressure and the acceleration they are pretty good up to about 2 or 300 Hz. What you are doing shows at least the accelerometer and at the end of your x-ray it seems like you had air in the skull. It looks like the accelerometer is moving differentially with respect to the skull, which is one of your conclusions. Potentially, during this test, what you're seeing is the effect of air inside and the brain moving without being directly connected the way it is in a fully pressurized subject.

A. I'm not sure I would entirely agree with that. The brain, or the CSF, is pressurized through the spinal cord and the system is effectively bled in an effort to remove all air before impact. I'd have to go back and look at the x-rays, but I was not aware, upon first examination, of any appreciable amount of air in the skull.

Q. You don't need very much in order for that phenomenon to occur.

A. At this point I can only say that that would bear further examination. To my knowledge, I'm assuming that that would not have affected the results too much, but I cannot particularly say because we did make every effort possible to remove any air from the cerebral spinal fluid.

Q. Sam Shaibani, Insurance Institute for Highway Safety
You mentioned that the x-ray taken before and after indicate that there was no displacement of the device. Do you get any feel for the fact that the movement during the impact may have affected your results? Was there any indication whether the wires were coiled

or not? Was there was any examination of the wires afterwards indicating any strain or any damage? How is that going to be monitored and controlled if you're going to extend this type of technique?

A. You're right that in this particular prototype device the wires were not coiled for this initial test.

Q. The point I'm trying to make is that if you detect any damage in the wires, how are you going to interpret that as far as the validity of the results is concerned?

A. Given the nature of these wires, specifically, teflon insulated wires, it would be very difficult to discern any damage to the transducer wires themselves, as teflon is a very difficult material to damage. In terms of being satisfied with the fact that the accelerometer did not move relative to surrounding brain tissue I'd say that first, we were only interested, in making sure that there was no gross relative motion. Obviously from these x-rays you can't make a precise statement. However, this particular cadaver suffered four rather severe impacts on that day. We were quite happy to see by the end of the day that apparently the transducer was still in, or had returned to, its starting position. The data suggested it had moved during the impact. However, it looked as though it had returned to its original position, from the x-rays.

Q. Shaibani

But on the results that you've given us there's plus 8 millimeters minus 12 millimeters, possible travel. That's 20 millimeters. Are the wires going to be able to accommodate that. You know that from whatever anchoring point that you've got, you may have wires swimming about?

A. That was the idea behind coiling the wires. Unfortunately, for this particular test they were not. In the future there will be an effort to coil the wires as shown on the original prototype. Even though that one is a dummy wire, that is the idea we had behind it.

Q. Pat Kaiker, UMTRI

I think you should come down to UMTRI and use the high speed x-ray cinimaradiagraph and run this experiment again, you might get some interesting data.

A. Yes. I've been recently familiarized with this particular type of device and also it would be interesting instead of using transducers to simply use neutral density markers for the same type of experiment.